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LUMINOUS TASMANIA: SEEING THE DARK IN A DIFFERENT LIGHT

by Lisa-ann Gershwin

(with fourteen plates and two tables)

Gershwin, L. 2022(i:xii): Luminous Tasmania: seeing the dark in a different light. *Papers and Proceedings of the Royal Society of Tasmania.* 156: 135–160. ISSN: 0080–4703. Glow Show Tasmania, Studio 3, 71 Murray Street, Hobart, Tasmania 7000, Australia. Email: lisa@glowshowtas.com

A resplendence of poets could not conceive of something so exquisite as the kaleidoscope of nature's nocturnal glow. For the first time, this paper presents an overview of Tasmania's luminous phenomena: the Aurora Australis, or Southern Lights; Sea Sparkles, or marine bioluminescence *Noctiluca scintillans*; Glow-worms *Arachnocampa tasmaniensis*; Ghost Mushrooms *Omphalotus nidiformis* and other fungi; fluorescent scorpions *Cercophonius squama;* fluorescent marsupials (14 species), placental mammals (five species), and monotremes (two species); fluorescent birds (eight species); and Goblin's Gold Moss *Mittenia plumula*. For each, I briefly detail their natural history, early Tasmanian history, notes on their occurrence in nature, and other aspects of interest. Many of these phenomena are little known in Tasmania and require further scientific inquiry. All have great tourism and educational potential and most of the living forms are under increasing threat for their survival.
Key Words: bioluminescence, biofluorescence, Aurora Australis, Dinoflagellata, Diptera, fungi, Arachnida, Marsupialia, Aves, Tasmania, citizen science.

INTRODUCTION

Author Jennifer Tsang wrote:

> *"In the darkness of the night, bioluminescent insects or mushrooms reveal themselves, oceans light up when disturbed, and the world turns into a hauntingly beautiful place. One could imagine this sight as frightful or surreal, and bioluminescence may even resemble ghosts or spirits to some. Bioluminescence has held a folkloric charisma since ancient times."* (Tsang 2017)

Luminescence comes in many forms, but this paper covers only three: aurora fluorescence, biofluorescence and bioluminescence (the prefix *bio-* meaning made by organisms).

Bioluminescence is one of the oldest fields of scientific study, dating back to the first written records of the ancient Greeks. Its history and wonder are masterfully captured by Princeton Professor E. Newton Harvey's 700-page epic *A History of Luminescence from the Earliest Times until 1900* (Harvey 1957). Aristotle's *De Anima* is the oldest surviving detailed scientific treatment of bioluminescence, where he compared it to lightning "when you strike the sea with a rod by night and the water is seen to shine" (Harvey 1957, p. 40), and described it as "things that appear fiery or shining" (p. 66) and "exhalations of fire from the sea" (p. 41). Two millennia later, the Danish physician Bartholin wrote *De Luce Animalium* (Bartholin 1647), a comprehensive treatment describing every luminescent phenomenon known at the time (real or imagined). In Bartholin's view, light is innate and ubiquitous and should be regarded as a fifth principle or element (Harvey 1957).

Bioluminescence is a chemical reaction of two substances, a substrate called a luciferin, and an enzyme called a luciferase, which catalyses the oxidation of luciferin resulting in the emission of light. French pharmacologist Raphaël Dubois coined the terms luciferin and luciferase from his hot and cold experiments with glowing pastes made first from click beetles and then with clams (Dubois 1885, 1887).

In comparison to bioluminescence, biofluorescence is a completely different process, where an organism is illuminated by the light of one colour (e.g., invisible ultraviolet), which transforms it to another (often visible) colour (Murthy & Virk 2014). The term fluorescence was coined by Cambridge Professor Sir George Gabriel Stokes (1852), to describe what he called dispersive reflection, where the wavelengths of dispersed light are always longer than the wavelength of the original light (Valeur & Berberan-Santos 2011). Stokes repeated the experiments of Sir John Herschel with prisms and quinine. As he moved a test tube filled with quinine solution past the visible spectrum, the solution remained transparent, but in the invisible part of the spectrum corresponding to ultraviolet, the quinine glowed a beautiful celestial blue. Stokes wrote of his experience: "It was certainly a curious sight to see the tube instantaneously lighted up when plunged into the invisible rays: it was literally visible. Altogether the phenomenon had something of an unearthly appearance" (Valeur & Berberan-Santos 2011, p. 733).

Biofluorescence had, in fact, been known, but unnamed, since 1565, when the Spanish physician and botanist Nicolás Monardes observed and reported unusual colouration in medicinal herbs brought to Europe from the West Indies (Lagorio *et al.* 2015). However, for the next 500 years, bioluminescence stole the limelight and even then, most of the research on (or with) fluorescence

has been at the cellular or tissue level (Lawrence 1954). The concept of whole animals fluorescing in psychedelic colours has hitherto been restricted to a few obscure papers … and cartoons.

As mesmerising as bioluminescence and biofluorescence are, to many, the aurora is even more so. The Roman philosopher Seneca wrote: "There are Chasmata (chasms), too, when there is a subsidence of some portion of the heavens, which sends out hissing flame, as it were, from its hidden recesses. There are also a great number of colours in all these. Some are of brightest red, some of light insubstantial flame, some of white light, some glittering, some with a uniform glow or orange without sparks or rays" (Harvey 1957, p. 38). The aurora is produced by fluorescence, similar to biofluorescence but in outer space and on a much grander scale.

Luminous phenomena have fascinated mankind since time immemorial and are reported in the earliest and most conspicuous scientific and historical documents. For example, a cave painting of the aurora in France dates back 30 000 years to Cro-Magnon Man (NASA 2006). The Biblical prophet Ezekiel had a vision around 593 BCE (Siscoe *et al.* 2002): "And I looked, and, behold, a whirlwind came out of the north, a great cloud, and a fire infolding itself, and a brightness was about it, and out of the midst thereof as the colour of amber, out of the midst of the fire" (Ezekiel 1:4). Aristotle called the lights in the night sky "chasmata"; he, and Seneca 300–400 years later, thought cracks in the sky allowed light or flames to penetrate from beyond the heavenly firmament (Lummerzheim 2021). Aristotle likewise pondered bioluminescence, as did Pliny the Elder in the first century CE, both expressing wonder about its cool properties (Harvey 1957, Lee 2008). Christopher Columbus was captivated by bioluminescence around Bermuda on the second-last day of his famous voyage where he "discovered" the New World in 1492 (Geggel 2012). Captain James Cook is credited with making the first written scientific record of the Aurora Australis, observing it on the night of 17 February 1773 during his second voyage to Australia; although there is credible evidence that he and others observed it prior to that date (Willis *et al.* 2009). Darwin marvelled at bioluminescence in the Canary Islands during the *Voyage of the Beagle* (Darwin 1839), and yet was troubled by the discontinuous distribution of "phosphorescence" across taxa (Campbell 2012).

Historically, the term "phosphorescence" was used as a catch-all for different types of luminescence. Today, phosphorescence is generally taken to mean "slow luminescence", where the glow lingers after the excitation light ends, compared to fluorescence as "fast luminescence", where the glow disappears as soon as the source is removed (Princeton Instruments 2005). Both require stimulation with an external light source, such as a UV torch.

To study things today that glow in the dark is to study human curiosity, superstition and divinity. It seems particularly fitting, therefore, that the 2008 Nobel Prize in Chemistry was awarded for the discovery and development of Green Fluorescent Protein (Nobel Prize 2008), which has not only changed the landscape of medical research, but also given us a way to stop tripping over our pets at night. The study of "glowy things" spans physics, geology, chemistry, history and biology, as well as ecology, biodiversity and evolution, in outer space, inner space and subterranean under-space. It covers living organisms, dead organisms and non-organisms.

It may seem ambitious to synthesise a paper on eight entirely different fields of study, each topic with its own body of literature but some may find it even more amazing in the macro view. For example, bioluminescence is found across the animal kingdom, from jellyfish and worms to squids and sharks, from fireflies to glow worms, across the plants and algae, fungi and bacteria. It is thought to have evolved independently at least 27 different times in marine fish alone (Davis *et al.* 2016). In fact, in one deep-sea study collecting more than 350 000 video observations across 17 years, over 75% of the individuals observed were bioluminescent (Martini & Haddock 2017).

AURORA AUSTRALIS

> *"To trace the story of the aurora through history is to trace the development of man from a creature of ignorance and superstition, through his renaissance of art and learning, to an analytical disciple of science and technology. But fortunately, man's transformation is not complete: Nature has contrived to clothe all objects of our scientific investigation, from the microscopic to the cosmic, in an aura of beauty and surprise. The aurora is perhaps the most spectacular of nature's contrivances to preserve the soul of the scientist."* (Eather 1980, preface, p. ix)

The Sun is a tempestuous body, roiling with violent outbursts in the form of sunspots, coronal holes, solar flares and coronal mass ejections, or CMEs (Palca 2013, Fox 2022, NOAA 2022). Sunspots are dark blotches on the Sun's surface below the corona; the dark spots result from cool regions caused by strong magnetic forces. Coronal holes are the hot, glowing outer layer of the Sun's atmosphere which some believe are the skeletons of old sunspots. Solar flares are short periods of explosive energy released from the Sun, travelling at the speed of light and taking eight minutes to reach the Earth. CMEs are like giant bubbles of hot charged plasma shot into space, which take one to three days to reach the Earth. Coronal hole winds are typically gradual, whereas CME winds are more of a jolt. CMEs are often accompanied by solar flares, but they are not the same. Aurorae can result from both.

The Sun's energy is carried towards the Earth on a stream of electrically charged particles (mostly protons and electrons) known as the solar wind (NASA 2002). The Earth's magnetic field deflects these particles as they approach, creating a cavity in the solar wind (the magnetosphere) and a large tail on the night side of the Earth, that is, away from the Sun. Energy leaks into the magnetosphere, and the aurora results from electrons in

the tail becoming unstable and losing energy. Most of our knowledge about the aurora comes from the northern hemisphere, but because it is a planetary phenomenon, we can assume that these principles hold true in the south.

Seasonality

One of the earliest scientific patterns to be recorded was the correlation between the aurora and the spring and autumn equinoxes, that is, that the aurora occurs most frequently around March–April and September–October annually (Young *et al.* 2022). The explanation for this semi-annual variation is in the orientation of the Sun's magnetic field (known as the *Bz component* and carried to Earth on the solar wind) relative to ours. When the solar wind's "north-south" component is more or less opposite the "north-south" component of the Earth's own magnetic field, this opens a hole thus allowing the solar wind to flow more easily towards Earth's magnetic poles. This is known as the *Russell-McPherron Effect* (Russell & McPherron 1973, Young *et al.* 2022).

It is also commonly believed that winter is "aurora season", stemming from the fact that there are more night-time hours during the winter, hence more hours in which the aurora may be seen. From the small collection of records listed below, as well as photographic records on social media, and this author's own experience, it is clearly possible to see the aurora during any season of the year.

Time of day

The aurora may be visible from early dusk to late dawn; however, it tends to be most intense and dynamic around solar midnight, or the point in the night where the Sun is equidistant between the dusk and dawn. This is due to the physics of the electrons leaking from the tail of the solar wind into the magnetosphere (the cavity in the solar wind on the night side), and from there into our atmosphere (NASA 2002). Moreover, according to the website AuroraBorealisObservatory.com, if you are located before solar midnight, the aurora expansion will most likely come from the east, but when you have passed solar midnight, the expansion will typically seem to come from the west. This is useful if you are looking for a location to take pictures of the expansion phase of substorms. Before midnight, choose a location that has your desired composition towards the east, and after midnight, towards the west (Hanssen 2021).

Interannual variation

Over time, the Sun's activity builds to a maximum, its magnetic field reverses, then activity settles back down to a minimum, and another cycle begins. This cycle, known as the Solar Cycle, occurs approximately every 11 years (NASA 2020). During a solar maximum, the Sun produces around three CMEs per day, whilst activity drops to one every five days or so near a solar minimum (Fox 2022). Our next solar maximum is expected to occur in July 2025 (NOAA 2020), so aurora activity is anticipated to increase up to then.

Colours

An aurora results from charged particles spewed out from the Sun and hurtled across space and its colours are determined by the interaction of several factors: the type of gas, the altitude and the solar particles (Aurora Live 2020, Lummerzheim 2021). Different atoms and molecules in the upper atmosphere interact with charged particles to produce characteristic wavelengths (colour) via fluorescence. Even though the most abundant gas in our atmosphere is molecular nitrogen, we most commonly associate the colours of oxygen with the aurora. At mid-altitudes (100–250 km), monoatomic oxygen (O) typically emits photons with a lemon-green glow, but together with blue N_2+ appears as more of a lime green colour. In a super-excited state at higher altitudes (beyond 250 km), oxygen may emit a red-orange glow. Diatomic nitrogen (N_2) emits deep red photons, while its ionised form (N_2+) emits a deep blue-purple glow. In the lower atmosphere (80–100 km above the earth), a pink glow results from a combination of red N_2 and blue N_2+.

The aurora may be visible as any of numerous different structures, including:

- a glow above the horizon, which may be green or reddish or both
- beams that shoot up into the sky and travel across the horizon
- giant blue rays of diffuse light (these are not yet well understood)
- arcs of light
- undulating curtains (uncommon in Tasmania)
- Strong Thermal Emission Velocity Enhancement (STEVE), an aurora-like beam of purple and green light, resulting from a ribbon of hot gases in the atmosphere.

The more vibrant the aurora, the more extreme the geomagnetic risk to the electricity grid and magnetic media. For example, a solar superstorm known as the Carrington Event in August/September 1859 produced a spectacular aurora but also wreaked havoc on telegraph systems around the world (Wikipedia 2022). So strong was the geomagnetically induced current that the telegraph between Boston and Maine was run with perfect communication for two hours on "celestial power", that is, without battery power (Boteler 2006, Green *et al.* 2006). In 2013, Lloyd's of London issued a report estimating the impact on America of a Carrington-level event at that time. Among their findings:

> *"The total U.S. population at risk of extended power outage from a Carrington-level storm is between 20–40 million, with durations of 16 days to 1–2 years. The duration of outages will depend largely on the availability of spare replacement transformers. If new transformers need to be ordered, the lead-time is likely to be a minimum of five months. The total economic cost for such a scenario is estimated at $0.6–2.6 trillion USD."* (Lloyd's 2013)

That estimate was a decade ago.

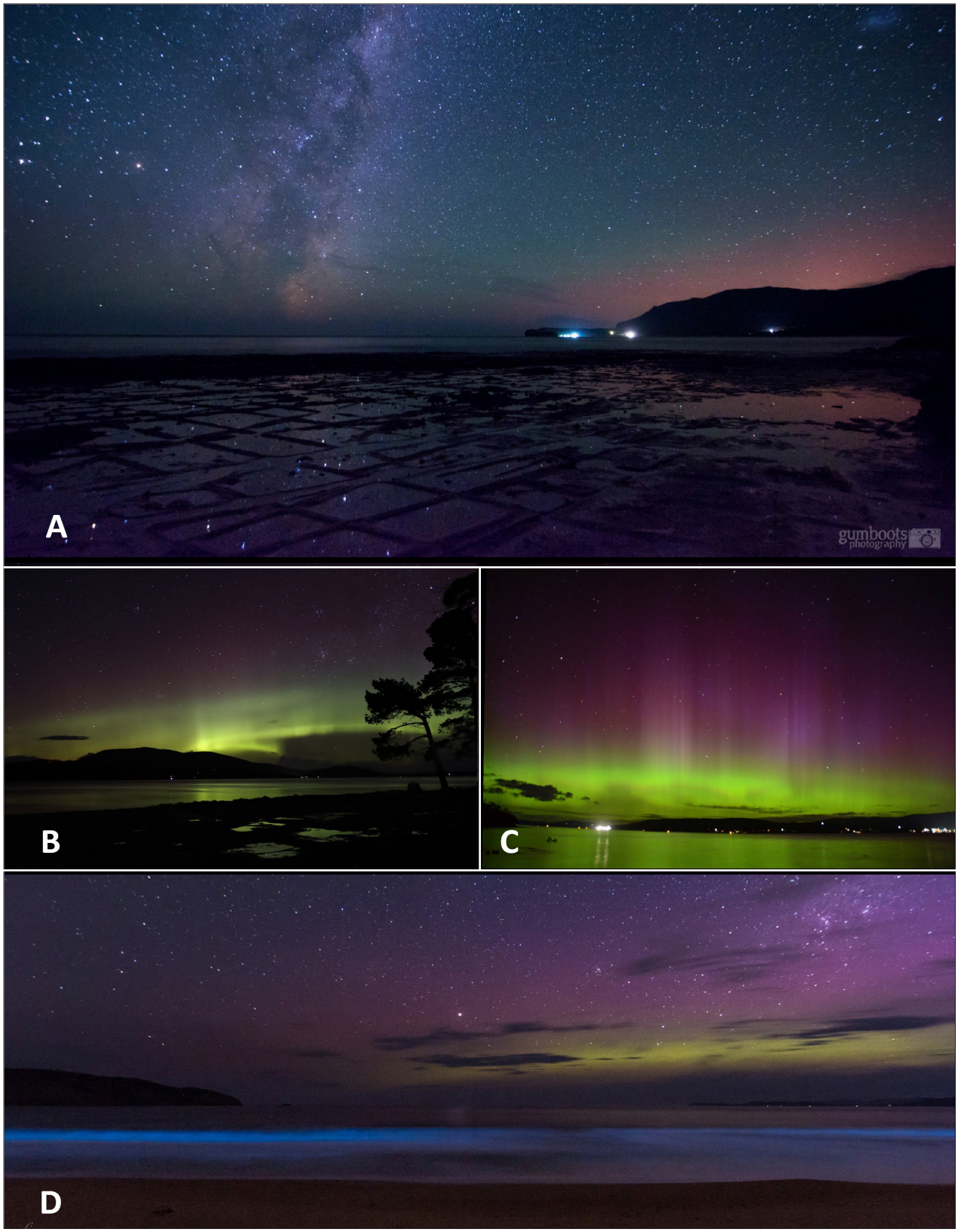

Plate 1 — Aurora Australis in Tasmania. **A** at Tessellated Pavement, copyright Fiona Gumboots Walsh; **B** at Gordon, copyright Luis Mora; **C** at Howden, copyright Lisa Gershwin; **D** with bioluminescence at Ralphs Bay, copyright Fiona Gumboots Walsh.

Using historical records dating back more than 2000 years, Lloyd's estimated the periodicity of a Carrington-level event of around 150 years, with a reasonable range of 100–250 years. The Carrington Event occurred 163 years ago. How a Carrington-level event would impact Tasmania is unknown, but we can reasonably expect it to be highly disruptive.

To reflect on Eather's (1980) evocative quote, it seems that the aurora may be nature's most glorious manifestation of both beauty and beast. Beauty, in the mesmerising lights that dance in the sky, and beast, in that the more vivid these lights are to our unaided eye, the greater the geomagnetic threat to humanity.

Early reports of the aurora in Tasmania

The Aurora Australis, or Southern Lights, is a common phenomenon in Tasmania's night skies (pl. 1) and has been recorded since the earliest times. In 1851:

> *"Mr. Milligan stated that he observed the Aurora of the 4th* [of September] *from 9 to 10 o'clock p.m., (when it began to wane), at Oyster Cove, in D'Entrecasteaux Channel; that in Hobart Town, the following evening, about half-past 9 o'clock, he observed a few faint auroral coruscations in the south; and that the aborigines reported the occurrence from 8 to 9 on the same evening of an Aurora of unusual brilliancy, displaying long shoots of red, blue, and green light, accompanied at intervals with a crackling noise, which they exemplified by snapping the fingers repeatedly."* (Milligan 1851, p. 161)

Other descriptions of the aurora in Tasmania include:

On 21 April 1858 the *The Sydney Morning Herald* reported:

> *"Aurora Australis. – This meteorological appearance, which is rather unusual in Tasmania, was visible on Friday night* [16 April]*, commencing shortly before ten o'clock. The Aurora was not very luminous, but sufficiently so to constitute a beautiful spectacle, the night being very clear and brightly star-light."* (Anonymous 1858, p. 8)

On 2 September 1859, simultaneously observed in Tasmania, Victoria, San Francisco, and across Europe, *The Argus* reported:

> *"AURORA AUSTRALIS AND BOREALIS. … calls your attention to the above phenomenon making its appearance here simultaneously with its appearance in Tasmania… This splendid phenomenon occurred with increased brilliancy last night. About half-past 3 in the afternoon the declination instrument at the Observatory, on the Flagstaff-hill, commenced to be disturbed very suddenly, and the intensity of all the phenomena from that time increased rapidly. Professor Neumayer at once predicted a magnetic storm, and soon after sunset an aurora was displayed such as has seldom been witnessed in the southern hemisphere."* (Anonymous 1859a, p. 6)

It is notable that the above aurora was the Carrington Event, the extreme solar storm discussed earlier. This CME was so powerful that it was believed to take only 17.6 hours to reach the Earth (compared to the more typical three days), and it was visible around the world, including lower latitude areas like Queensland, Hawaii, Cuba, and even Colombia, close to the equator. In the Rocky Mountains, it was so bright that it fooled miners into thinking it was morning, and in northeastern United States people could read a newspaper by its light (Wikipedia 2022).

On 13 December 1859 *The Sydney Morning Herald* reported for Hobart:

> *"THE AURORA AUSTRALIS. – …appeared in great magnificence on Tuesday night at Hobart Town. It reached from the western to the southern and south-eastern horizons. At about ten o'clock, and from that to half-past ten, it was most brilliant. …The light swept upwards to the meridian in long streamers, much like the tail of a comet, and across these there fluttered brilliant corruscations rolling upwards like the waves on the shore. But the most splendid effect was seen at about a quarter-past ten, when from behind the south-western end of Mount Wellington a beautiful stream of rose-coloured light shot upwards to the meridian, gradually collapsing into a narrow strip, very brilliant, and of the colour of carmine. … We have never seen a more splendid Aurora than this."* (Anonymous 1859b, p. 3)

On 9 August 1917 in Hobart, Launceston and Zeehan, reported in *The Mercury*:

> *"AURORA AUSTRALIS. OBSERVED IN TASMANIA. A FINE SPECTACLE. An exceptionally fine display of the natural phenomena known as the Aurora Australis or 'Southern Lights' was seen in various parts of Tasmania last evening. In Hobart it became visible at about 6.30 p.m., when the whole of the southern sky became a brilliant pink. At first the glare seemed as though it were caused by a huge bush fire, but it gradually spread until it extended over nearly half the sky with rays of light shooting out in all directions and constantly appearing and disappearing. … OBSERVED AT LAUNCESTON. ... The illumination covered about half the sky, stretching from the zenith to the horizon from a little north of west to just south of east. On the western edge there was a shaft of bright light resembling a huge searchlight, widest at the horizon and terminating in several shifting points well up the dome. …The display lasted for more than a quarter of an hour and was watched by a large number of citizens. … THE SIGHT ON THE WEST COAST. ZEEHAN. Shortly after 7 to-night a magnificent view of the Aurora Australis could be*

Plate 2 — Bioluminescence in Tasmanian Sea Sparkles *Noctiluca scintillans*. **A** daytime surface slicks at Bellerive Yacht Club; **B** nighttime bioluminescence at Marieville Esplanade. Both copyright Lisa Gershwin.

Plate 3 — Bioluminescence in Tasmanian Glow-worms *Arachnocampa tasmaniensis*. **A** in daylight, copyright Daniel Dirks; **B** bioluminescence, Jon Sullivan CC iNaturalist.

> *obtained, and the spectacle was visible for nearly an hour. It was crimson and illuminated the southern clear starlit sky from the horizon to the zenith. Luminous arches frequently changed their shape, forming boreal crowns, and rays of changing tints rose perpendicularly, and appeared and disappeared, and moved slowly eastward. … It was the finest sight witnessed on the West Coast in the memory of the oldest inhabitants."* (Anonymous 1917a, p. 4)

This same event was also observed in Wynyard, reported in *The North Western Advocate and the Emu Bay Times*:

> *"AURORA AUSTRALIS. Several beautiful views of the Aurora Australis were visible in Wynyard on Thursday evening, and many people left their tea to gaze heavenwards at this picturesque phenomenon, with its varied hues. …"* (Anonymous 1917b, p. 3)

Of course, many other aurorae have been observed in Tasmania since.

Finding the Aurora Australis in Tasmania

The Aurora Australis is fairly common in Tasmania and may be viewed throughout the state, most often by looking south.

Understanding Alerts. It is now possible to receive alerts of impending or current auroral activity. Numerous aurora apps and government space weather sites issue alerts, and most include information on six values and indices that are helpful in understanding the likelihood of an aurora. These are summarised below, with more thorough explanations on the websites Solar Ham (https://www.solarham.net/) and Dark Sky Finder (https://darksitefinder.com/reading-aurora-charts/).

KP Index: A measure of geomagnetic activity in the Earth's atmosphere, expressed in three-hour increments, and the corresponding width of the auroral oval, or the latitudes where the aurora will be visible. KP comes from "Planetarishe Kennziffer", German for "planetary index". A higher KP index means the aurora will be visible at lower latitudes. For example, in general terms, a KP 3 may be seen on camera in southern Tasmania, a KP 4 is likely to be seen on camera throughout Tasmania and may be seen faintly with the naked eye, a KP 5 may reveal more structure with the naked eye and brilliantly on camera and, anything higher is likely to be spectacular in Tasmania.

G Index: A measure of the strength of a geomagnetic storm. KP 5 through 9 are elevated to a storm classification scale, where KP 5 is considered a G1 storm, KP 6 corresponds to a G2 storm, and so on.

Solar Wind Speed: The speed of the charged particles streaming from the Sun. Its baseline is normally around 300 km/sec. Typical windspeed during an aurora will be in the 500–600 range but may exceptionally reach more than 1000 km/sec. In general, the higher the windspeed, the more vivid and dynamic the display.

Bz: A measure of polarity of the Sun's magnetic field carried through the solar system by the solar wind (the Interplanetary Magnetic Field, or IMF). The Earth's magnetic field points north. When the Sun's magnetic field (IMF) points sharply south, it may cancel the Earth's magnetic field, creating an opening for the solar wind to reach our atmosphere. Thus, the more strongly the Bz component is trending south, the more likely it is for a stronger aurora to form.

Bt: A measure of the strength of the IMF, with higher strengths being more favourable.

Density: A measure of the energetic particles of the solar wind (per cm^3); in general, a density of 10 or higher is favourable.

SEA SPARKLE

> *"The sea was luminous in specks & in the wake of the vessel, of a uniform, slightly milky colour. – When the water was put into a bottle, it gave out sparks for some minutes after having been drawn up. – When examined both at night and next morning, it was found full of numerous small (but many bits visible to the naked eye) irregular pieces of (a gelatinous?) matter. The sea next morning was in the same place equally impure."* (Charles Darwin, Beagle Zoology Notebook, first two handwritten entries in Campbell 2012, p. 449)

Marine bioluminescence is found all over the world, from the Arctic to the Antarctic, from beaches to the open ocean and deep sea. It is so common, that several places have formed tourism industries around their bioluminescence: Luminous Lagoon in Jamaica, Halong Bay in Vietnam, Bioluminescent Bay at Grand Cayman, and Bahía Bioluminiscente (aka Mosquito Bay), Laguna Grande and La Parguera in Puerto Rico.

Marine bioluminescence in Tasmania

Many marine species are capable of bioluminescence. "Sea Sparkle" in the Tasmanian context generally refers to the invasive dinoflagellate *Noctiluca scintillans*. Blooms of *Noctiluca* follow a predictable pattern: they begin with a small estuarine seed population, feast on diatom blooms responding to upwelling or other nutrient input, surface and starve in calm water, then form red surface slicks as they die (Hallegraeff *et al.* 2020). Bioluminescence is associated with this last stage, that is, their die off (pl. 2).

Whereas the aurora is both beauty and beast in outer space, so too, is the Sea Sparkle in inner space. Beauty, in the incredible displays of bioluminescence that it gives off en-masse, and beast, in its triple impact of toxicity, low oxygen and plankton consumption (Hallegraeff *et al.* 2019). *Noctiluca* is an invasive pest that competes with and consumes other species higher in the food chain (Quevedo *et al.* 1999, Umani *et al.* 2004). India provides a cautionary tale, where hypoxia-enhanced *Noctiluca* blooms feed on diatoms, they in turn are fed on by jellyfish blooms, which also consume zooplankton (do Rosário Gomes *et al.* 2014, Thomas *et al.* 2020) and hence the greater *Noctiluca*'s

intensity and duration, the greater its threat to the local fisheries and ecosystems.

History of Sea Sparkle in Tasmania

Along Australian shores, the species most likely to be observed luminescing is the cosmopolitan red tide forming heterotrophic dinoflagellate *Noctiluca scintillans* (Latin for "sparkling nightlight"). *Noctiluca* was first reported in Australia in 1860 from Sydney Harbour (Bennett 1860). Reports from the 1930s and 1950s considered it to be just a minor part of the plankton, and confined to east coast estuaries, respectively (Hallegraeff *et al.* 2008). It wasn't until 1982, some 120 years after the species was first observed, that its first Australian "red tide" event was reported, this time in Lake Macquarie hundreds of kilometres to the north of its original record (Ajani *et al.* 2001). By the 1980s, it had reached north Queensland; by 2008, Western Australia and South Australia; and by 2014, the Northern Territory (Hallegraeff *et al.* 2020). Today, *Noctiluca* frequently forms spectacular blooms up and down the New South Wales coastline, especially around Jervis Bay (FB Group 2022).

In Tasmanian waters, *Noctiluca* was first observed in March 1994 and has been growing its distribution since (Hallegraeff *et al.* 2008). Driven by climate warming, it is expanding southward by around 40 km per year; and by 2010, it had penetrated the Southern Ocean (McLeod *et al.* 2012). Tasmanian research has determined that *Noctiluca* can reproduce at 10°C and survive at 7°C but is unable to thrive at 25°C (Hallegraeff *et al*. 2019). Research in Germany found that *Noctiluca* can survive below 0°C (Elbrachter & Qi 1998) meaning that Tasmanian water is well within *Noctiluca's* preferred parameters: for example, the sea surface temperature at Hobart ranges between a high of 18.1 and a low of 11.9°C (https://www.seatemperature.org/australia-pacific/australia/hobart.htm).

Under normal circumstances, that is, in relatively low numbers, *Noctiluca* is generally not overly dangerous (Hallegraeff *et al.* 2020). However, surface slicks with concentrations of 1–2 million cells per litre can be hazardous to aquaculture and fisheries due to high ammonia and reduced oxygen (Hallegraeff *et al.* 2019). For example, a seven-month-long bloom event off Tasmania's east coast in 2001–2002 posed a significant threat to the aquaculture industry, particularly salmon (Hallegraeff *et al.* 2008). Anecdotal evidence exists of shellfish tasting like ammonia when associated with *Noctiluca* slicks (Hallegraeff *et al.* 2020). Moreover, field and laboratory observations on *Noctiluca* grazing demonstrate that it consumes toxic dinoflagellates; its harmful effects may therefore be magnified when the phytoplankton community becomes dominated by dinoflagellate assemblages (Escalera *et al.* 2007).

Large blooms of *Noctiluca* occur occasionally in Tasmania. The previously mentioned one, for example, lasted from September 2001 off the east coast to March 2002 off Nubeena (Hallegraeff *et al.* 2008). Another of this species' spectacular blooms here was first reported in May 2015 in Ralphs Bay on South Arm (Gershwin *et al.* 2015). Primarily confined up to this point to scholarly appreciation, the 2015 bloom "went viral". The bloom was first found by aurora chasers, who initially became frustrated with the blue lights in the water interfering with their aurora photos, until they realised the source. This bloom caused a media sensation, and within days, thousands of people were flocking to this remote beach on cold autumn nights to observe this incredible natural phenomenon (Salmon 2015).

GLOW-WORMS

While William Shakespeare (1599–1601) and William Wordsworth (1849) waxed poetic about glow-worms, species in Tasmania have very little in common with their European forms. European glow-worms are more widely known as Fireflies. Northern hemisphere glow-worms are larval and adult female beetles (Order Coleoptera), *Lampyris noctiluca* (Linnaeus, 1767), that glow a brilliant yellow-green. In contrast, the Australian and New Zealand glow-worms, are the cave-dwelling snare-forming larvae of fungus gnats (Order Diptera), *Arachnocampa* spp., that glow magnificently blue and demonstrate why common names are not always the most useful way of communicating about species.

While Shakespeare asserted that the glow-worm's light is "uneffectual", bioluminescence is in fact one of the most efficient types of light known: "Nearly all of the energy input into the reaction is transformed into light. The reaction is 85%–90% efficient. As a comparison, the incandescent light bulb only converts about 10% of its energy into light, and a 150 lumen per Watt LED converts 20% of input energy to visible light" (Singh *et al.* 2018, pp. 27–61).

Bioluminescence in dipterans is restricted to the fungus gnats (Mycetophilidae: Keroplatinae) (Sivinski 1998). The most well-known of these are in the genus *Arachnocampa*, meaning "spider web grub" in reference to their sticky snares. Eight are found in Australia and one in New Zealand (Baker 2010). Only one is identified in Tasmania, *Arachnocampa tasmaniensis* (Ferguson 1925). Varying degrees of the morphology and life cycle are well documented for three species: New Zealand's *A. luminosa*, Queensland's *A. flava* and *A. richardsae* from New South Wales (Gatenby 1959, 1960; Richards 1960, Harrison 1966, Stringer 1967, Baker & Merritt 2003, Meyer-Rochow 2007). The duration of growth phases differs from species to species. In general, the glow-worm spends around nine months in its bioluminescent larval stage, living in a hollow, tubular horizontal runway of silk and mucus, from which it suspends a chandelier-like snare of sticky threads for catching prey attracted by its posterior glow. Once they reach a mature size, 30–40 mm, larvae pupate, this stage lasting a few weeks. The adult gnat hatches and lives only a few days and does not feed; its sole focus is to find a mate. Eggs incubate for a few weeks, before hatching into the larval glow-worm stage. The biology of *A. tasmaniensis* is probably similar.

Bioluminescence is produced internally in their Malpighian tubules, branches from the gut that normally

function as insects' kidneys but are modified for light production (Chandler & Baker 2009). In the Fandango animated film, *Surf's Up*, a lava-boarding scene memorably portrayed two penguins falling into a pool of glow-worm poo (https://www.youtube.com/watch?v=YHirkSmJcEU). This led to online sources claiming that glow-worms don't defecate; instead, their solid and liquid metabolic wastes are used as fuel for producing light (Gardner 2009). It's an amusing proposition, but according to entomologist and glow-worm expert David Merritt of the University of Queensland, "There is no evidence that waste materials are used in producing the light" (Merritt 2022).

History of glow-worms in Tasmania

The first glow-worm described in Australia was in fact *A. tasmaniensis* from the Ida Bay Caves in Tasmania's far south (Ferguson 1925). Even before its original description, high profile accounts of glow-worms in Tasmania were published. Johnston discussed finding glow-worms at the caves at Ilfacombe (now Flowery Gully) near Beaconsfield in his *Systematic Account of the Geology of Tasmania* (Johnston & Etheridge 1888), and an anonymous author recounted in *Scientific American* discussion about glow-worms at Ida Bay during a meeting of the Royal Society of Tasmania (Anonymous 1891). The species is now known from many locations around the state (Goede 1967, Baker 2010).

Glow-worms are common in caves and cave-like habitats, that is, dark, still habitats with very high humidity (pl. 3). These include abandoned mines and railway tunnels, rainforests, leafy glades and grottos, damp overhangs like roadcuts and trail cuts, and even under verandas. Glow-worms are strongly associated with permanent streams, either cave streams or surface streams (Goede 1967). Plowman *et al.* (2013) outlined the history and ecology of glow-worms in Australia and New Zealand and provided local information on Tasmanian sites and species.

Research on the circadian rhythms of Tasmanian glow-worms has revealed fascinating insights. Firstly, they may be seen at any time of day but typically glow most brightly in the late afternoon rather than at night (Merritt 2022). Secondly, the glow-worms within a single cave will synchronise their light-dark cycle with each other, but the populations in different caves have different cycles (Merritt & Clarke 2011, Maynard & Merritt 2013). At Ida Bay, for example, pupae and adults are strongly seasonal, commonest in spring and summer, with their increase in numbers tied to the increase in food capture in the larvae's snares (Driessen 2010). The larvae are present throughout the year, but their glow cycles differ. Mystery Creek Cave glow-worms glow most abundantly from late spring through to autumn, while those at Exit Cave have no consistent seasonal pattern (Driessen 2010). Multi-day timelapse digital photography at Mystery Creek has shown that larvae located outside the cave or at the cave mouth luminesce only at night, whereas those located deeper inside the cave glow most strongly in the afternoon (Merritt *et al.* 2012). Intriguingly, Tasmanian glow-worms can start glowing at any part of the day-night cycle, compared to Queensland's *A. flava*, which is locked into nocturnal luminescence (Merritt *et al.* 2012).

Glow-worm larvae are highly sensitive to lights other than their own. In general, glow-worms will stop glowing when exposed to 1–5 minutes of white light and require on average around 30 minutes to recommence glowing, reaching pre-disturbed glow intensity by around 70 minutes (Mills *et al.* 2016). Experiments with one-minute exposure to other colours of light suggest that there are no safe colours of light to use with glow-worms: their reaction to blue light was similar to white, while red or green lights caused somewhat less disturbance but ultraviolet (UV) caused more (Mills *et al.* 2016). To determine whether cave lighting associated with tourism ventures has a deleterious effect on the glow-worms' wellbeing, a study comparing bioluminescence in viewing chambers and "unvisited" chambers in Marakoopa Cave in Tasmania's north, concluded that in carefully controlled situations with a limited number of brief exposures, the glow-worms did not appear to be impacted by the lighting (Merritt & Clarke 2013).

Tasmania is well-suited to glow-worms, due to the prevalence of limestone formations, and thus caves. The middle to upper Ordovician Gordon Limestone is widespread through western Tasmania and accounts for over 90% of Tasmanian caves (Goede 1967). In his thesis, Stefan Eberhard studied more than 130 caves in 31 karst areas, representing around 14% of the known caves and half of Tasmania's cavernous karst areas (Eberhard 1992). However, some of these caves have been historically under threat. At Ida Bay, for example, a limestone quarry (Blayneys Quarry) operated near Mystery Creek Cave during the Second World War, and another limestone quarry, Benders Quarry, was closed in 1992 because of its deleterious impacts on the Exit Cave system (Eberhard 1995, Eberhard 1999).

The world's entomofauna are in conservation crisis. A recent review concluded that almost half the world's insect species are rapidly declining and a third are threatened with extinction (Sánchez-Bayo & Wyckhuys 2019). Glow-worms in England have declined 75% in less than 20 years (Gardiner & Didham 2020). Snare-forming glow-worms are highly sensitive to changes in their habitat. Natural threats include winter flooding, predation by other cave fauna and fungal disease, while human threats include touching of larvae or their snares, air quality issues like carbon dioxide from visitors' exhalations or smoke disturbance from fires, changes in water quality affecting food supply, or changes in cave microclimate including, importantly, desiccation (Merritt & Clarke 2013). It is imperative that management guidelines are in place for their reservation and protection, and authorities can limit visitations to glow-worm sites to protect these fragile species (Glow Worm Tunnel Management Committee 2020).

GHOST MUSHROOMS AND OTHER LUMINOUS FUNGI

Our fascination with bioluminescence in fungi dates back thousands of years (Harvey 1957, Lee 2008). In their paper, 'Early accounts of fungal bioluminescence', Dean Glawe and Winton Solberg take the reader on a journey through European science, from Boyle's proof in the mid-1600s that luminous wood requires air to produce light, to Bacon's observations later that century on the essential similarity of the luminescence of wood and other objects, to Heller's demonstration two centuries later that the light emanating from decayed wood is fungal in origin (Glawe & Solberg 1989). The reader is treated to American philosopher Cotton Mather's attempt to harmonise science with religion, using fungal bioluminescence to show that "even the most objectionable and troublesome characteristics of plants can be beneficial", as part of his argument to infer the existence of a purposeful Creator. We are then treated to understanding the context of Olaus Magnus's solution to the long nights of Scandinavian winters by using rotten bark to produce light (Glawe & Solberg 1989, pp. 296–299).

Gates and Ratkowsky's *A Field Guide to Tasmanian Fungi* details 650 species (Gates & Ratkowsky 2016), and estimate that a further 300–400 are known here (Genevieve Gates, pers. comm. August 2022). Of these thousand or so species, members of the Facebook groups *Tasmanian Fungi* and *Bioluminescence Tasmania* have found three species that luminesce, plus another species that may, outlined below, with more still awaiting discovery.

Fluorescence in fungi has been known for decades, and indeed, has been used as a reliable taxonomic character by numerous workers (e.g., Reinhold 2020 synopsis). Gill (1995) reported that the flesh of Australian *Dermocybe* was "intensely fluorescent when viewed in U.V. light". More recently, Reinhold (2020) detailed the fluorescence of 14 species of fluorescent fungi from just 12 nights exploring in and around Cairns. Other than these reports and social media postings by a few dedicated naturalists, it appears that fungi fluorescence has been all but ignored in Australia, and particularly in Tasmania.

Ghost Mushroom

Ghost Mushroom (*Omphalotus nidiformis* (Berk.) O.K. Mill. 1994) is by far the largest and commonest of the fungi known to luminesce in Tasmania (pl. 4a, 4b). It is a gilled basidiomycete primarily found in two disjointed populations in southern Australia, one in southwestern Western Australia and the other in much of eastern Australia. It is generally found in temperate forests, but more than 4000 records in the Atlas of Living Australia (ALA) indicate that its distribution ranges from Port Lincoln in South Australia to Mowbray Forest Reserve in Julatten, Far North Queensland, including throughout much of Tasmania, as well as a record from Lord Howe Island in June 2019 (ALA 2022). It has also been reported from Norfolk Island (Cooper 2011) and Kerala, India (Shirmila & Radhamany 2012). As its specific epithet suggests (*nidus* is Latin for nest), its fruiting bodies are nest-shaped, funnel-shaped, or fan-shaped. They grow to 30 cm diameter, though typically much smaller. Dead or dying stumps, trees and logs of eucalypts and pines are the most frequently reported hosts. The caps come in two colour morphs, most commonly cream-coloured with a golden or orange central depression, or smoky grey, purplish or black; the whitish or cream-coloured lamellae run the length of the stipe.

The first account of the species we now recognise as *Omphalotus nidiformis* was in an 1841 letter by the Scottish naturalist James Drummond to Sir William J. Hooker, published the following year in the latter's *London Journal of Botany* (Drummond 1842). Before any name had been given to the species, Drummond described a specimen around 25 cm across and weighing more than two kilograms; this was similar in form to some small specimens found 6–7 years earlier growing on the stump of a Banksia tree near a Perth jetty on the Swan River. Both were remarkable for their brilliant luminescence. Subsequently, the species was described by the English naturalist Miles Joseph Berkeley (1844) based on Drummond's observations.

The following year, similar material was collected by the Tasmanian botanist Ronald Campbell Gunn, and forwarded to Berkeley, who described it as a different species, *Agaricus (Pleurotus) phosphorus* (Berkeley 1848). In all, Berkeley named at least four different forms of large glowing mushrooms from southern Australia, which have since been synonymised, and after a lengthy period of nomenclatural instability, *O. nidiformis* was given its present classification by Orson K. Miller, where it has remained since the late twentieth-century (Miller 1994).

Ethnobotanist Philip A. Clarke of Adelaide discussed the Aboriginal connection to fungi, including *O. nidiformis*. "In Aboriginal Australia it was widely believed that certain species of fungi retained power from their connection with the heavens…. Falling stars appear to be associated with the idea of evil magic in many tribes" (Clarke 2015, pp. 23–37). Clarke explained that some tribes believe that mushrooms are fallen stars and look upon them as being endowed with evil magic. He then recounted the story of Drummond, who showed a glowing specimen of *O. nidiformis* to local Aboriginal people, whereupon they cried out 'Chinga!', their name for a spirit and seemed much afraid of it (Drummond 1842). Similarly, the Koombumerri people of the Springbrook Plateau in southeast Queensland believed that the glowing fungi were the spirits of their ancestors and that it was disrespectful to look at them (Maguire 2011).

The ecological driver for luminescence in *O. nidiformis* is under debate. It is generally assumed that *O. nidiformis* luminesces to attract prey as a means of spore dispersal, as in other species (Oliveira *et al.* 2015, Weinstein *et al.* 2016). Indeed, it is confirmed as a host for fungus beetles (Fearn 2017), and in situ, *O. nidiformis* typically appears nibbled with different sized chunks missing, along with beetles and millipedes often milling about. Weinstein and his colleagues, however, called the spore dispersal hypothesis into question based on its autumnal fruiting season in their region being out of sync with summertime

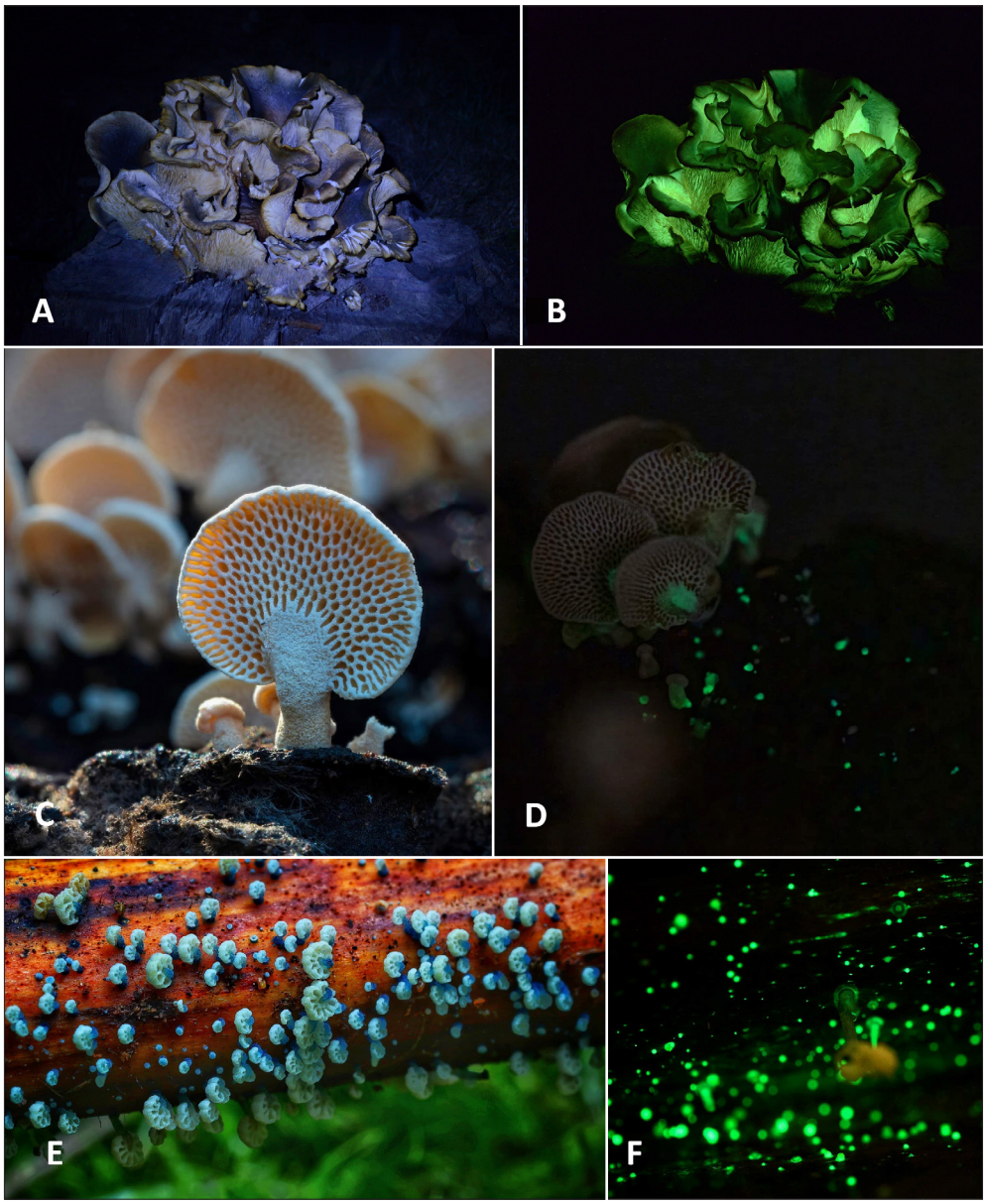

PLATE 4 — Bioluminescence in Tasmanian mushrooms. **A**, **B** Ghost fungus *Omphalotus nidiformis*, both copyright Lisa Gershwin; **C**, **D** Ping Pong Bats *Panellus pusillus*, both copyright Ryan Shan; **E**, **F** Tiny Blue Lights *Mycena azulina*, both copyright Bronek Burza. A, C and E white light, B, D and F natural bioluminescence.

peak insect periods, its use of constant luminosity rather than a diurnal rhythm, and their experimental results with flying insect attraction (Weinstein *et al.* 2016). But they conducted their experiment in the wintertime when one might expect less insect activity. Moreover, their experimental design seems open to question as they attached a cut piece of glowing fungus above one corner of a double-sided sticky trap which seems incongruous with methods of other studies. For example, Sivinski (1981) placed his glowing samples as close as possible to their original position, with the controls 80 mm to the side. By this standard, much of Weinstein's trap was a control. Another example is that of Oliveira and his colleagues (Oliveira *et al.* 2015), who covered their model fungi with scentless glue and measured the insects that landed on the glowing object itself rather than underneath it. The extent to which Weinstein's results would be repeatable in other conditions is unclear. For example, would their seasonality assumptions still hold true in areas like Tasmania, where *O. nidiformis* may occur any time of year, especially in the warmer months? Or, for example, might their cut pieces of fungus have exuded a chemical repellent of some sort, or might there have been an effect of hanging their sticky trap and fungus above the ground that was not accounted for?

A high level of community interest in these fascinating fungi has even led to a tourism industry built around *Ghost Mushroom Lane* in South Australia. This family-friendly site is within a commercial pine forest operated by Forestry SA, comprising a series of seasonal walking trails with evocative names like Fungi Hunter Alley and Neon Forest. Intense interest in Tasmanian *O. nidiformis* by photographers and

citizen scientists has led to a wealth of reports especially via the Facebook site *Bioluminescence Tasmania*, broadening our understanding of its seasonality. It has now been reported fruiting in every month in Tasmania, particularly from October through June.

Little Ping Pong Bats

As its common name suggests, this species *Panellus pusillus* (Pers. ex Lév.) Burds. & O.K. Mill. (a.k.a. *Dictyopanus pusillus* (Pers. ex Lév. Singer) resembles a tiny ping pong bat (pl. 4c, 4d). The fruit is flat and broadly round, with an array of tiny pores occupying the underside. It is typically found in large groups on stumps or wet wood. This species has more than 20 observations on the ALA, from across Tasmania dating from March 2001, though its luminescence has been known for more than half a century (Corner 1954, Wassink 1979). There is some discussion as to the real identity of Australian *Panellus cf pusillus*. Chew *et al.* (2015) discussed earlier authors' concerns about morphological anomalies in old world *P. pusillus*. Their own morphological and molecular analyses led them to distinguish their Malaysian specimens from Florida and Louisiana material, describing their form as *P. luxfilamentus*. Without explaining their reasoning, they stated, "*Panellus luxfilamentus* has been commonly misidentified as *Panellus pusillus* in Asia, Australia and New Zealand" (p. 185). Whether the Tasmanian form is the same as those found on the mainland, and conspecific with the Malaysian form, is unclear.

Tiny Blue Lights

The species *Mycena lazulina* Har. Takah., Taneyama, Terashima & Oba (2016) was only recently described in 2016 from Japan (Takahashi *et al.* 2016). It grows gregariously, with each fruit resembling a tiny dog's paw print, or wagon wheel. The stem is blue and its bioluminescence is green (pl. 4e, 4f). The first Tasmanian report was made on the Facebook site *Tasmanian Fungi* on 14 May 2021 (https://www.facebook.com/groups/tasfungi/permalink/2507723592707103/), discovered growing on a dead fallen rachis of the fern *Dicksonia antarctica* in the northwest.

Bitter Oyster

The species of fungi *Panellus stipticus* (Bull.) P. Karst, is known to be bioluminescent elsewhere but although the ALA lists over 100 observations of this species in Tasmania, it is yet to be confirmed to luminesce here (Gates & Ratkowsky 2016). According to ALA and other search sites, luminescence is well-known in eastern North American strains but not in those from elsewhere. Where it does luminesce, light is produced along the edges of the gills and where they join the stem and cap.

Biogeographical analysis using the ribosomal ITS region suggests that the species comprises two major clades, one from the northern hemisphere and the other from Oceania, with the New South Wales population basal to Tasmania and New Zealand (Jin *et al.* 2001). The Tasmanian population has 29 deleted base pairs compared to the northern hemisphere collections; whether this will ultimately result in a non-bioluminescent form, or an entirely different form, is yet unknown.

FLUORESCENT SCORPIONS

Fluorescence in scorpions under ultraviolet (UV) light was first reported about 70 years ago in Italy (Pavan 1954). That same year, another study on 18 species of arthropods across five classes and 13 orders, including scorpions, showed that 15 species fluoresced, ranging from mildly to brightly (Lawrence 1954). It is now thought that most scorpions fluoresce (Yoshimoto *et al.* 2020), enabling its wide use as a collection tool (Stahnke 1972) and as an aid to visualising their surface structure (Volschenk 2005). Scorpions are so strongly fluorescent, they continue to fluoresce when preserved in alcohol and even make the alcohol glow (Lawrence 1954, Rubin *et al.* 2017). Fluorescence in amber-fossilised scorpions has been widely reported in popular webpages (Kids Discover 2015), but the only reference to this is probably based on the findings of Rubin *et al.* (2017), who concluded that fossilised scorpions possessed the hyaline layer of the cuticle, a feature that appears to be associated with cuticular UV fluorescence. As is often the case with biofluorescence, compounds in the cuticle (or the shell, skin, or hair) are stimulated by UV light. Specific molecules absorb electromagnetic radiation (light) at shorter wavelengths that we can't see and re-emit it at longer wavelengths that are then visible. In the case of scorpions, the dominant compound is β-carboline, a tryptophan derivative, which produces an intense aqua colour when stimulated (Stachel *et al.* 1999).

Numerous hypotheses have been proposed as to *why they glow*, including acting as sunscreen, luring prey, finding mates or protection from parasitic infections (Lourenco & Cloudsley-Thompson 1996, Gálvez *et al.* 2020, Yoshimoto *et al.* 2020). However, the current widely accepted theory, from researchers in California is that fluorescence of the scorpions' own bodies enables them to detect UV light (such as on moon-lit nights), allowing them to make decisions about their activity levels (Kloock *et al.* 2010). Researchers from Oklahoma followed up with behavioural experiments on scorpions with blocked eyes under different light regimes and concluded that scorpions use their whole body as a photon-collector, transducing the UV light to the eerie colour, before relaying this signal to the brain, where decisions are made about detecting shelter (Gaffin *et al.* 2012).

History of fluorescent scorpions in Tasmania

Only one species of scorpion is known to occur in Tasmania, the Forest Scorpion or Wood Scorpion, *Cercophonius squama* (Gervais 1844) (pl. 5a, 5b). The species was first described from Van Diemen's Land as *Scorpio* (*Telogonus*) *squama*, before being moved to its present classification by Peters (1861). *Cercophonius squama* grows to 25–45 mm in length and is typically found in leaf litter or under logs. Like most other

species of scorpion, it is viviparous (Miller 2002). It is found throughout southern Australia in a disjunct population, with one population in southern Western Australia, and the other population in eastern Australia from the Eyre Peninsula in South Australia to north of Cairns in Queensland, including Tasmania (Carter & Murray 2020). To my knowledge, fluorescence in *C. squama* has not yet been studied.

FLUORESCENT MARSUPIALS, PLACENTALS, AND MONOTREMES

Eight years after Wood's lamp (the UV torch) was invented, the ethnologist and professor of medicine Hans Stübel (1911) studied rabbits, the edible frog *Rana esculenta*, a range of human tissues and numerous organic compounds from albumen to urine, concluding that "all animal cells and tissues have the property of fluorescing in ultraviolet light. … Only the presence of pigment or of hemoglobin and hemoglobin derivatives can impair or cancel this phenomenon. … Like the animal tissues, most of the organic compounds which compose them show a more-or-less strong fluorescence" (translation by Linda Reinhold, used with permission). Fluorescence was discovered in New World opossums in the 1970s and well characterised in the 1980s, with three-fourths of the species collectively displaying a psychedelic range of colours, including maroon, cinnamon (red orange), yellow, peach, pink, lavender, purple and blue (Pine & Abravaya 1978, Meisner 1983, Pine *et al.* 1985). However, this phenomenon in marsupials had already been described long before in Brushtail Possums *Trichosurus vulpecula* by Bolliger (1944), with one of the fluorophores even identified (Nicholls & Rienits 1971). (Fluorophores are fluorescent molecules that absorb light at a given wavelength and re-emit light at a higher wavelength, producing fluorescence in various colours.)

On 16 October 2020, a discovery published in the journal *Mammalia* was of Platypus *Ornithorhynchus anatinus* biofluorescing under UV light (Anich *et al*. 2021). The story propagated through the public's imagination as it swept the world's media and in rapid succession, fluorescence was confirmed in a range of marsupials and other mammals: Wombat sp. *Vombatidae*, Bilby sp. *Macrotis*, and Echidna *Tachyglossus aculeatus* (Edwards 2020), then the Tasmanian Devil *Sarcophilus harrisii*, bandicoot and bat species (Readfearn 2020). In fact, a zoologist in North Queensland had already been researching this very same question and had published on it prior to and independent of the Platypus discovery (Reinhold 2020).

In August 2022, it was announced with much public interest that the Thylacine *Thylacinus cynocephalus* was also fluorescent (Kean & Cutting 2022) and was the lead story on ABC news on the day of its announcement. While this finding is certainly exciting – given the prevalence of fluorescence in the marsupials it was to be expected. However, this discovery was made with the use of a microscope. Toussaint *et al*. (2022) found that when examined spectroscopically, all mammal fur emitted a blue photoluminescence, which, given its ubiquity, could be due to the amino acid residues in keratin or to intrinsic deep blue autofluorescence (Millington 2020). Autofluorescence is a process whereby biological and non-biological structures may naturally emit light. Pine *et al*. (1985) had noticed a similar phenomenon when fur was examined microscopically, even if no fluorescence was visible at the whole-pelt scale. My examination of a museum Thylacine mount with a dim 395 nm UVA light suggested pale blue fluorescence, especially on the neck, leg and ear. In life, the neck and ear displayed patchiness of paler highlighting, and the leg displayed pale blue compared to a distinctly purplish light beam shining on the table under the specimen; these colour differences were also apparent on my iPhone 13 Pro. On my computer screen, however, the neck and ear patchiness were largely smoothed out and the purplish beam on the table looked only marginally darker blue than the leg, highlighting a serious limitation with researching and documenting subtle colour differences. Whether these differences would be more apparent with another wavelength, or in the dark, or with a stronger light, etc., remains unknown, and we may never know whether a Thylacine would have fluoresced in life, in a way comparable to the psychedelic colours of its relatives, visible to the unaided eye under UV torchlight. As most tissues and organic substances fluoresce, autofluorescence is an obvious complication in fluorescence microscopy. However, outside the laboratory, this phenomenon is not yet widely known.

Given the prevalence of fluorescence in marsupials and other mammals, the obvious question is why. Conceivably, standing out to predators or prey could have its limitations to such an extent that one could easily imagine that natural selection would eliminate it rather quickly. Kohler and her colleagues (2019) observed that vivid pelage fluorescence is ubiquitous in the placental New World Flying Squirrels in the genus *Glaucomys*, leading them to propose four hypotheses as to why. Firstly, fluorescence is an adaptation to their nocturnal–crepuscular environment. *Glaucomys* squirrels are active at twilight and night and do fluoresce (108/109 museum specimens in three species), whereas 26 specimens of three species of diurnal sciurids did not fluoresce, strongly suggesting a functional adaptation to low-light environments rich in UV wavelengths. Secondly, fluorescence is important in snow-covered landscapes, given that snow cover reflects UV, amplifying its importance. Thirdly, fluorescence is used in intraspecific communication, specifically in its ventral prominence allowing *Glaucomys* to signal to one another as they glide among trees. And fourthly, fluorescence is useful in antipredator behaviour, either as a form of Batesian mimicry with co-occurring fluorescent owls or as camouflage in the squirrels' UV-saturated, fluorescing lichen-covered environment.

In Tasmanian marsupials, ventral fluorescence is particularly pronounced in bandicoots, which are entirely ground dwelling, so none of the above explanations seem to apply. As this same conundrum was noted by Reinhold (2020) for Queensland bandicoots, without resolution, more research is needed to help reveal the reasons why.

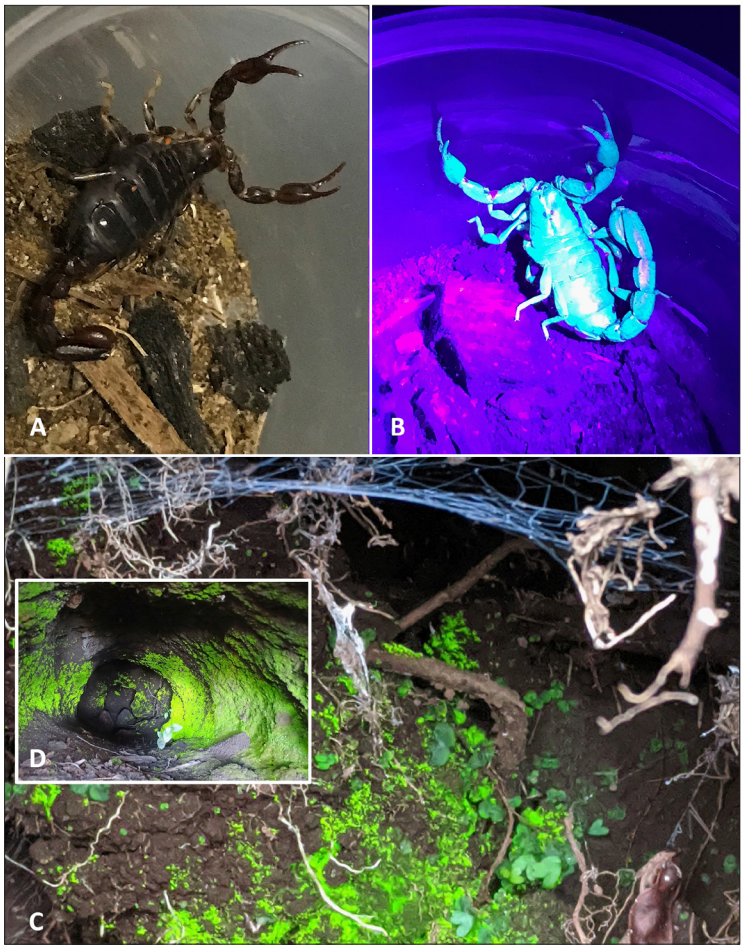

Plate 5 — Luminescence in Tasmanian scorpions and moss. **A**, **B** Fluorescent Forest Scorpion *Cercophonius squama*, left in indoor light, right, fluorescence under UV light, both copyright Lisa Gershwin; **C**, **D** Luminescent Goblin's Gold Moss *Mittenia plumula*. C, from Loongana, Tasmania, copyright Brenda Marshall. D (inset), for comparison, in a wombat burrow, New South Wales, copyright Tony Markham.

Plate 6 — Fluorescence in Tasmanian marsupials. **A** Tasmanian Devil *Sarcophilus harrisii*; **B** Eastern Quoll *Dasyurus viverrinus*; **C** Spotted-tail Quoll *Dasyurus maculatus*. Note ears fluorescing dark blue under UV light. All copyright Lisa Gershwin.

History of fluorescent marsupials, placentals and monotremes in Tasmania

Other than the previously mentioned accounts of the Tasmanian Devil and species coincidentally found in Tasmania, my own investigation on whole-animal fluorescence in roadkill and museum specimens has yielded some cautiously optimistic results. A summary of these observations, coupled with previous media reports, is presented in table 1.

The dark blue ears of the Tasmanian Devil (pl. 6a) are of a strikingly similar colour to that found by the Toledo Zoo in their live animal (Readfearn 2020), and both species of Quolls *Dasyurus* had a similar dark blue ear colouration (pl. 6b, 6c) to the devil, which differed markedly from other species' light blue ears. Moreover, the light blue ears of the Eastern Barred Bandicoot *Perameles gunnii* were similar in both museum and roadkill specimens (pl. 7a–f), and to those of other museum specimens including roadkill Pademelon *Thylogale billardierii*. Despite these similarities, it cannot be discounted that the museum fluorescence was due to an artifact of the preservation process, or something inherent to the skin. Notably, Bolliger (1944) found that the skin of the Brushtail Possum was coated with a substance that fluoresced sky blue and easily flaked off. Whether this may explain the light blue ears of so many of the museum specimens is unknown.

It is intriguing that the only species tested by the author so far that did not fluoresce was the Platypus *Ornithorhynchus anatinus*, across numerous museum specimens, whereas Anich *et al.* (2021) found that their American museum specimens (originally from Tasmania) fluoresced brightly. Reinhold (2020) found that her Platypus roadkill specimen fluoresced faintly. The two museum specimens briefly examined by the author showed almost no fluorescence, except for a faint dark green shimmer on the toes of one. The difference in fluorescence expression between the faint colour change in Reinhold's recently dead specimen and the strong glow of the American museum's long-dead specimen is counter-intuitive, suggesting other factors could be operating. For example, in the American specimens, fumigants required for exportation, may have led to a brighter fluorescence than elsewhere.

It is clear from even these limited observations that fluorescence is potentially widespread in Tasmanian marsupials and other mammals (pls 6–12). Where I have had the opportunity to compare museum specimens with freshly killed specimens, the differences are striking. For example, the Eastern Barred Bandicoot museum specimen displayed bright white and light blue ears but no colouration of the pelage, whereas two different freshly-killed specimens displayed an other-worldly, vibrant, almost shimmery orange-pink coat. This brilliant colour was most startlingly visible with the 395 nm torch but was also plainly discernible under 365 nm. While I am confident in my roadkill observations, it is possible that taxidermy chemicals and museum fumigants may give misleading results with fluorescence in museum specimens and this requires further study.

A NOTE ON FLUORESCENT BIRDS

Conceptually, luminous birds have been on the minds of scientists and philosophers for centuries (McAtee 1947). In the first century CE, for example, Pliny included luminous birds from the Black Forest of Germany in his *Naturall Historie* but suspected them to be an unfounded rumour (Pliny & Holland 1634). Later, during the Middle Ages, the German monk and naturalist Albertus Magnus included Pliny's birds with glowing wings, and Professor Conrad Gesner of Zurich, writing in *De Lunariis*, the first book devoted to luminescence, also included luminous birds without scepticism (Harvey 1957). In fact, as Harvey later wrote, "Practically all the great naturalists, and others who wrote in lighter vein, believed in luminous birds" (p. 67).

Strange and unexplained luminous phenomena have sometimes been attributed to birds, like the *Will-o'-the-Wisp* in England and the *Min Min* lights in Australia (Silcock 2006). *Will-o'-the-Wisp* is a phantom light floating in the air over swamps and bogs, supposedly leading travellers into trouble. *Min Min* lights are ghostly orbs seen hovering in the outback. These remain enigmatic questions to be answered by ecophysiologists, if not cryptozoologists.

While bioluminescence in birds is yet to be confirmed, fluorescence may in fact be relatively common. For example, Weidensaul *et al.* (2011) used it to routinely age the flight feathers of owls and observed that numerous species of owl tested by them and others all fluoresced. Similarly, Arnold *et al.* (2002) studied fluorescent signalling in Budgerigars *Melopsittacus undulatus* and a survey of nearly 1000 bird species, covering all orders, found high proportions exhibiting UV-reflecting feathers (Mullen & Pohland 2008). George Pohland studied the fluorescent plumage of two bird species from Tasmania, the Green Rosella *Platycercus caledonicus* and Orange-bellied Parrot *Neophema chrysogaster* (Pohland 2007) but did not provide details on their appearance under UV light.

Blythman *et al.* (2016) examined 74 Australian birds in six species (three Stringiformes and the remainder in the Caprimulgiformes), which fluoresced. Of these, the Tawny Frogmouth *Podargus strigoides* occurs in Tasmania, however, while the Australian Owlet-nightjar (*Aegotheles cristatus*) on the mainland fluoresces, whether the Tasmanian subspecies (*A. c. tasmanicus*) does, has yet to be tested. I only cursorily examined a few species of birds in a museum exhibition, and found fluorescence in eight, primarily in the feet and toes (table 2, pls 13–14). Whether this skin fluorescence was an artifact of the taxidermy process is unknown; but the findings are consistent with Stübel's (1911) observation that all biological tissues fluoresce. However, unexpectedly, a few other birds I tested for fluorescence with 395 nm UV did not produce any detectable result, including the Kookaburra *Dacelo novaeguineae* and the Eastern Rosella *Platycercus eximius*. The exhibition was lit, however, so a darker room or different wavelength of UV light may yield different results.

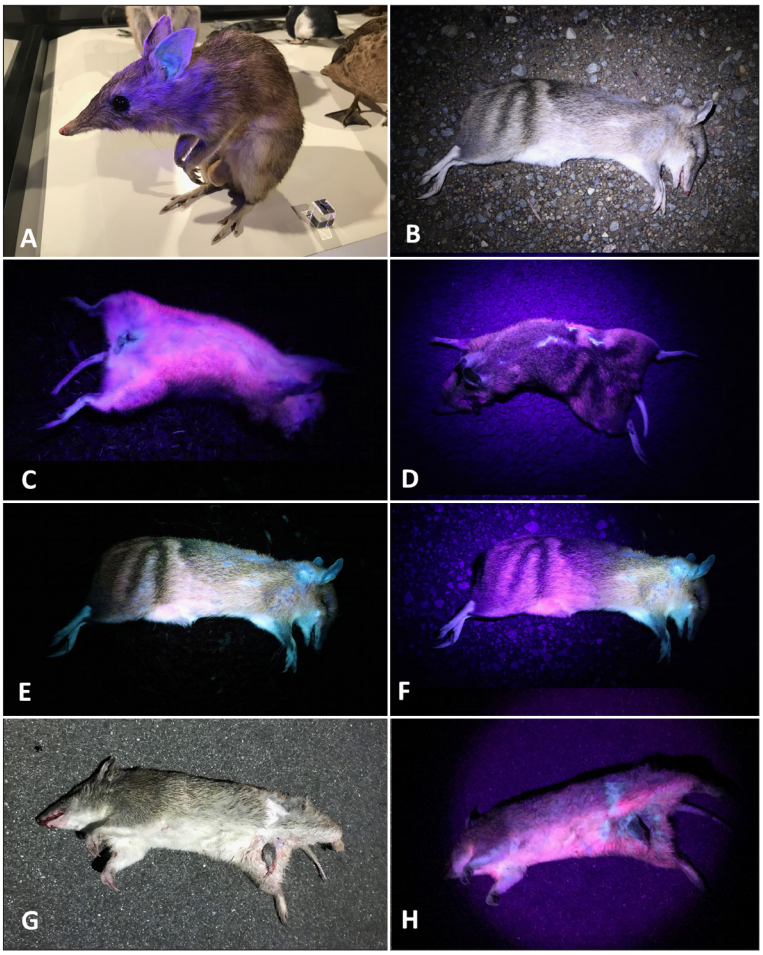

Plate 7 — Fluorescence in Tasmanian marsupials. **A**–**F** Eastern Barred Bandicoot *Perameles gunnii*; **G**–**H** Southern Brown Bandicoot *Isoodon obesulus*. A, museum specimen, note ears fluorescing blue under UV light. B-H, road-kill. B, G, white light, C-F, H, note intense fluorescence under UV light, C, D, H 395nm UV light; E, 365nm, F, 395nm on left and 365nm on right. Photos B-F copyright Luis Mora; A, G-H copyright Lisa Gershwin.

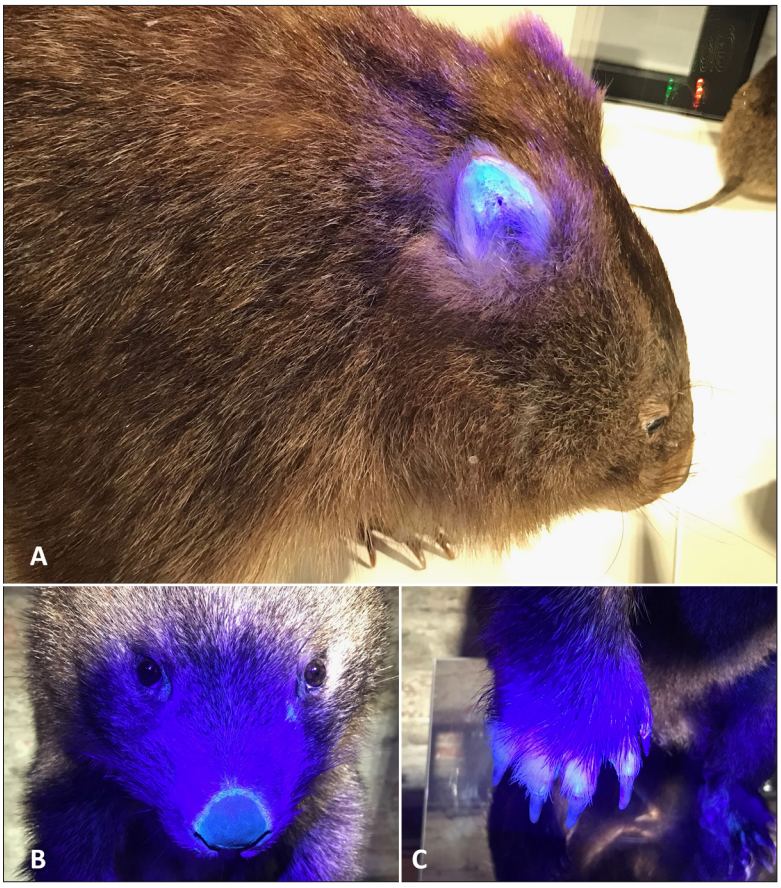

Plate 8 — Fluorescence in Tasmanian marsupials. Wombat *Vombatus ursinus*. Museum specimen, note turquoise and white fluorescing under UV light. **A** ears; **B** nose; **C** toes. All copyright Lisa Gershwin.

TABLE 1 — Summary of fluorescence in mammals found in Tasmania

Species	Fluorescence	Reference
Fluorescent Tasmanian Monotremes		
Platypus *Ornithorhynchus anatinus*	Bright blue-green fur and skin Some fur dull moss green Faintly dark green toes	Anich *et al.* (2021) Reinhold (2020) Museum specimen
Echidna *Tachyglossus aculeatus*	Bright whitish quills	Dr Kenny Travouillon Twitter 28 Nov. 2020; Museum specimen
Fluorescent Tasmanian Marsupials		
Tasmanian Devil *Sarcophilus harrisii*	Violet-blue ears	Readfearn (2020) Museum specimen
Eastern Quoll *Dasyurus viverrinus*	Violet-blue ears	Museum specimen
Spotted-tailed Quoll *Dasyurus maculatus*	Violet-blue ears	Museum specimen
Thylacine[1] *Thylacinus cynocephalus*	Bright blue bands on fur shaft under a fluorescent microscope; ? Turquoise ear, body and leg fur	Kean & Cutting (2022) Museum specimen
Eastern Barred Bandicoot *Perameles gunnii*	Light blue ears; Magenta belly, side fur, and between stripes on back; ears light blue	Museum specimen and roadkill
Southern Brown Bandicoot *Isoodon obesulus*	Orange-pink fur on underside, lighter on belly, deeper on thighs and biceps	Museum specimen and roadkill
Wombat *Vombatus ursinus*	Green fur; Light blue ears and skin around nose, white paws, dark green nose	Edwards (2020) Museum specimen
Brushtail Possum *Trichosurus vulpecula*	Sky blue skin; hairs many colours Blue hair Green fur Pink fur around face, neck, and belly	Bolliger (1944) Nicholls & Rienits (1971) ZIP (2018) Roadkill
Ring-tail Possum *Pseudocheirus peregrinus*	Brilliant white belly fur and white portion of tail, pale turquoise	Roadkill
Little Pygmy Possum *Cercartetus lepidus*	Turquoise ears and paws	Museum specimen
Krefts Glider *Petaurus breviceps*	Light blue fur on underside Turquoise ears and paws	Reinhold (2021a) Museum specimen
Bennetts Wallaby *Macropus rufogriseus*	Blue-green hind legs, dark blue paws, bright turquoise tail and inner ears	Roadkill
Pademelon *Thylogale billardierii*	Turquoise and white ears	Roadkill
Tasmanian Bettong *Bettongia gaimardi*	Pale blue ears, eye skin, mouth, and hind legs	Museum specimen
Fluorescent Tasmanian Placentals		
Lesser Long-eared Bat *Nyctophilus geoffroyi*	Turquoise ears and fur around eyes	Museum specimen
Broad-toothed Rat *Mastacomys fuscus*	Turquoise nose	Museum specimen
Swamp Rat *Rattus lutreolus*	Turquoise lower and upper lips, nose, inner ears, and penis	Museum specimen
Water Rat *Hydromys chrysogaster*	Turquoise lower lip and toes	Museum specimen
Long-tailed Mouse *Pseudomys higginsi*	Turquoise lower and upper lips and nose	Museum specimen

The extent to which the fluorescence in museum specimens was natural fluorescence or an artifact of the taxidermy process is unknown. [1] Indicates uncertainty, discussed in text.

A NOTE ON GLOWY MOSS

The luminescent moss *Mittenia plumula* (Mitt.) Lindb., often called "Goblin's Gold", was reported (https://www.facebook.com/groups/275373059316490/search/?q=Mittenia%20) from Loongana in Tasmania in November 2020 (pl 5c, 5d). Some debate about its identification and taxonomy followed on the website *iNaturalist* (https://inaturalist.ala.org.au/observations/64989974), leading the naturalist who posted it to withdraw the identification. The question remains unresolved. The species' luminescence, however, is somewhat misleading, attributable to refraction rather than true bioluminescence or biofluorescence.

In Australia, this moss is most often found in wombat holes, while it frequents rabbit holes in New Zealand, and in caves it sparkles and gleams over the ground as if numerous emeralds were scattered about (Glenny 2020). The New Zealand Biota website quotes a most lovely account of Goblin's Gold by Austrian botanist Anton Kerner von Marilaun (1887; translated by Crum (1973, p.147):

> *"If we reach curiously into the depth of the grotto to snatch a specimen of the shining objects and examine the prize in our hand under a bright light, we can scarcely believe our eyes, for there is nothing else but dull lusterless earth and damp, mouldering bits of stone of yellowish-grey color! Only on looking closer will it be noticed that the soil and stones are studded and spun over with dull green dots and delicate threads, and that, moreover, there appears a delicate filigree of tiny moss-plants. This phenomenon, that an object should only shine in dark rocky clefts, and immediately lose its brilliance when it is brought into the bright daylight, is so surprising that one can easily understand how the legends have arisen of fantastic gnomes and cave-inhabiting goblins who allow the covetous sons of earth to gaze on the gold and precious stones, but prepare a bitter disappointment for the seeker of the enchanted treasure; that, when he empties out the treasure which he hastily raked together in the cave, he sees roll out of the sacks, not glittering jewels, but only common earth."*

A NOTE ON OTHER GLOWY THINGS

An incredible diversity of Tasmanian species beyond those covered here are likely to fluoresce. Many amphibians fluoresce (Taboada *et al.* 2017, Lamb & Davis 2020, Reinhold 2021b), but to my knowledge none here have been tested. So too, a significant biodiversity of arthropods is already known to fluoresce, so it is possible that all terrestrial animal phyla are known to have at least one or more members that fluoresce (Lagorio *et al.* 2015, Jeng 2019), and that with further study these numbers may increase.

An emerging fascinating area of study is the co-occurrence of bioluminescence and biofluorescence (Jeng 2019). It seems that the cells involved with one often do double duty with the other. Given our range of bioluminescent species, it therefore seems plausible that some may also be fluorescent.

CONCLUSION

Tasmania's luminescent organisms offer an inherently fascinating way of understanding the natural world and the escalating pressures they face in a rapidly changing environment. Glow-worms are so susceptible to climate-related desiccation, fire smoke, food supply and human impact, that we may well lose them in the future. Glowing fungi may seem stable because their main fungal mass is hidden underground, but they require a delicate balance of moisture disrupted by climate warming as well as the burning of their habitat. Sea Sparkle, in contrast, is an

TABLE 2 — Summary of fluorescence in birds found in Tasmania

Species	**Fluorescence**[1]	**Reference**
Tawny Frogmouth *Podargus strigoides*	Hot pink flight feathers (underside) Turquoise toes	Blythman *et al.* (2016) Museum specimen
Galah *Eolophus roseicapilla*	Pale blue beak and skin around eyes	Readfearn (2020)
Masked Owl *Tyto novaehollandiae castanops*	Pale blue skin around eyes, base of beak, and feet; magenta feathers on underside of wings	Museum specimen
Wedge-tailed Eagle *Aquila audax fleayi*	Bright turquoise toes	Museum specimen
Lyrebird *Menura superba*	Pale blue toes and base of beak	Museum specimen
Cape Barron Goose *Cereopsis novaehollandiae*	Minty green feet	Museum specimen
Black Swan *Cygnus atratus*	Pale blue skin around eyes and beak (but unexpectedly, not the feet)	Museum specimen
Little Penguin *Eudyptula minor*	Light blue belly feathers and toe feathers	Museum specimen

[1] Whether the fluorescence observed in museum specimens was true fluorescence or an artifact of the taxidermy process is unknown.

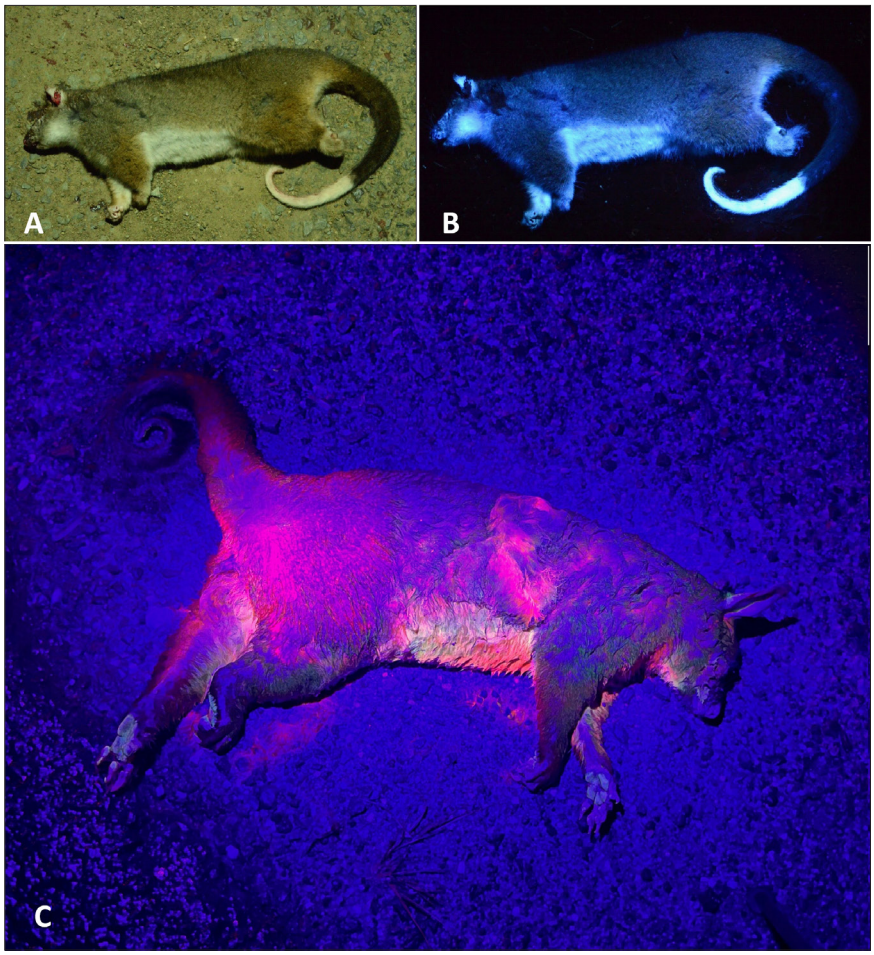

Plate 9 — Fluorescence in Tasmanian marsupials. **A**, **B** Ring-tail Possum *Pseudocheirus peregrinus*, Roadkill, note ears, belly, and white tail tip fluorescing bright white under UV light; **C** Brushtail Possum *Trichosurus vulpecula*, Roadkill, note body fluorescing pink under UV light. All three copyright Lisa Gershwin.

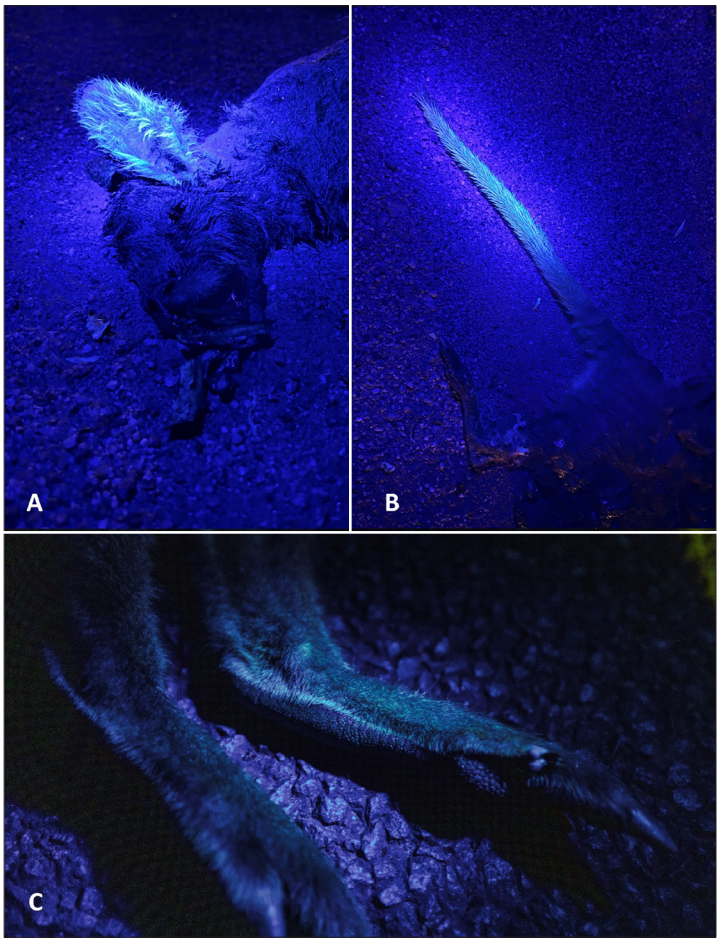

Plate 10 — Fluorescence in Tasmanian marsupials. Bennetts Wallaby *Macropus rufogriseus*. Roadkill. **A** Note fluorescing ear; **B** Note fluorescing tail; **C** Note legs fluorescing dark green under UV light. A, B copyright Lisa Gershwin C, copyright Toby Schrapel.

Plate 11 — Fluorescence in Tasmanian marsupials and monotremes. Museum specimens. **A** Krefts Glider *Petaurus breviceps*, note bright blue ears and paws fluorescing under UV light; **B**, **D** Pygmy Possum *Cercartetus lepidus*, note turquoise fluorescent ears and paws; **C** Echidna *Tachyglossus aculeatus*, note bright whitish fluorescent quills. All copyright Lisa Gershwin.

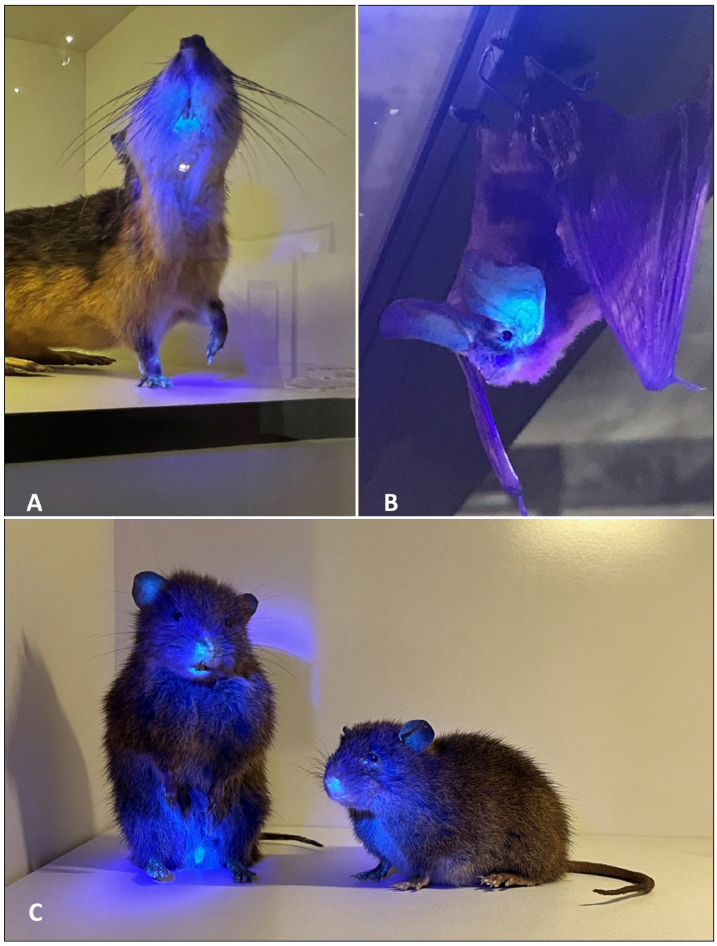

Plate 12 — Fluorescence in Tasmanian placental mammals. Museum specimens. **A** Water Rat *Hydromys chrysogaster*, note fluorescing face and feet; **B** Long-eared Bat *Nyctophilus geoffroyi*, note ear and eye fur fluorescing; **C** Swamp Rat *Rattus lutreolus*, note ears, nose, hind feet, and penis fluorescing turquoise under UV light. All copyright Lisa Gershwin.

Plate 13 — Fluorescence in Tasmanian birds. Museum specimens. **A** Tasmanian Masked Owl *Tyto novaehollandiae castanops*; **B** Lyrebird *Menura superba*; **C** Tawny Frogmouth *Podargus strigoides*. Note UV light-stimulated pale blue fluorescence of skin around eye and upper beak in A, and of pale green fluorescence of feet in B–C. All copyright Lisa Gershwin.

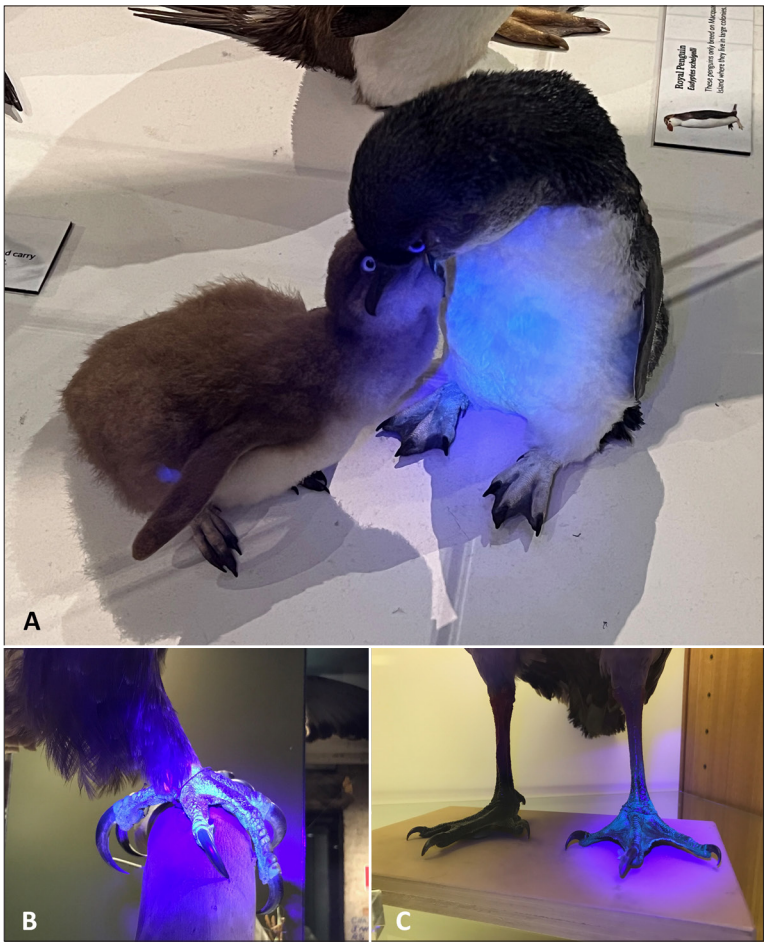

Plate 14 — Fluorescence in Tasmanian birds. **A** Little Penguin *Eudyptula minor*; **B** Wedge-tail Eagle *Aquila audax fleayi*; **C** Cape Barron Goose *Cereopsis novaehollandiae*. Note UV light-stimulated blue fluorescence of belly feathers in A, and of pale green fluorescence in feet of B–C. All museum specimens. All copyright Lisa Gershwin.

introduced marine pest which thrives in Tasmania's over-nutrified coastal ecosystems, and the wildlife carnage on Tasmanian roads speaks the truth about the fight our native animals are losing. Even scorpions and mosses, considered by most as unwanted pests, may garner appreciation when seen in this new light.

With new information emerging especially about fluorescent and bioluminescent organisms, we are very much at the dawn of understanding the glowing world around us. This is a wondrous age of adventures in luminescence that are in the grasp of citizen scientists and those who contribute to image-driven databases like *iNaturalist* or *QuestaGame* are not only having fun but helping build scientific knowledge to such an extent that they may rightly be considered parascientists.

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